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INTERPLANETARY MAGNETIC FIELD

by

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ABSTRACT

IMP 2 magnetic field measurements in the magnetosheath and in interplanetary space have been compared with polar magnetic disturbances. Ground disturbance on a 2.5 minute time scale is represented by the universal time index AE prepared from the digitized magnetograms of six auroral zone observatories. The AE index is compared to the satellite field measurements for intervals totaling more than 600 hours in October and November 1964. Investigation of the magnetosheath or interplanetary directions distributions when ground conditions are quiet or disturbed shows that southward fields are associated with disturbed conditions and northward fields with quiet times. Large disturbances are found to correspond almost exclusively to southward fields and especially to large southward fields. The results indicate the importance of the magnetic field in the coupling mechanism which allows solar wind plasma energy to be converted into energy associated with the ionospheric currents of the auroral electrojet. The results support the reconnection field model where interplanetary field lines connect to geomagnetic field lines producing plasma flow in and around the magnetosphere which drives the high latitude currents.

Introduction

Numerous studies comparing satellite and ground measurements have been made in an effort to understand the mechanisms by which the solar wind produces geomagnetic disturbance and related effects. The solar wind plasma contains almost all of the energy which must be used in driving the currents which produce geomagnetic activity and indeed solar wind velocity has been found to correlate with geomagnetic activity as measured by the K_p index (Snyder et. al., 1963). The strength of the interplanetary field has also been found to correlate with K_p (Wilcox, et. al., 1967; Schatten and Wilcox, 1967) and the direction of the field has been shown to be important (Fairfield and Cahill, 1966; Wilcox, et. al., 1967; Zelwer, et al., 1967; Rostoker and Fälthammar, 1967).

The purpose of this paper is to use a large amount of IMP 2 data to further investigate the role of the interplanetary magnetic field in producing high latitude geomagnetic disturbance. A new index of ground activity is used which permits quantitative, high time resolution studies heretofore impossible with the K_p index or original magnetograms. The analysis confirms the earlier results which indicated the importance of both field magnitude and the north-south component of the interplanetary field in producing disturbance. The relative importance of field strength and direction is emphasized. Results are interpreted as supporting Dungey's reconnection model of the magnetosphere.

Satellite and Ground Data

The IMP 2 satellite was launched on October 4, 1964 with an apogee of $15.9 R_E$ (earth radii) which initially was near the earth-sun line. The orbital period was approximately 35 hours so that the spacecraft spent up to one day per orbit beyond the magnetopause early in its lifetime. As the earth moved around the sun the orbit moved toward the dawn meridian in solar ecliptic coordinates at the rate of 1° per day with the result that the satellite progressively spent less time outside the expanding magnetopause. Data presented in this paper is from the first 40 orbits when the satellite was in the local time region of 0800-1200. During this interval over 325 hours of interplanetary data and 345 hours of magnetosheath data were obtained.

The IMP 2 magnetic field experiment was identical to that flown on IMP 1 one year earlier (Ness et. al., 1964). The experiment consisted of two monoaxial fluxgate magnetometers which independently made vector magnetic field measurements as the satellite spun. The analysis techniques have been discussed previously (Fairfield and Ness, 1967), and the possible error limits have been estimated as $\pm 10\%$ in magnitude and $\pm 8^\circ$ in angle. Vector measurements were obtained every 20.5 seconds but in the work discussed here, the averages over 5.46 minute intervals were used for comparison with ground magnetic data which were available on a 2.5 minute time scale.

Comparison of satellite and ground magnetic data in the past has necessitated use of either the three hour K_p (or a_p) indexes or original magnetograms. Use of the 3 hour indexes precludes the detailed study of time variations such as bay events or substorms

which occur on time scales typically of one or two hours. On the other hand use of a representative selection of original magnetograms is tedious, often subjective, and incompatible with a large scale quantitative statistical study.

A third alternative has been used in the present study which overcomes these disadvantages. The AE (auroral electrojet) index first defined by Davis and Sugiura (1966) has been prepared for the lifetime of IMP 2. Preparation of this index involved the use of 2.5 minute digitized H (or X) magnetogram traces from the six arctic auroral zone observatories shown in Table 1. First zero base levels were obtained at each station by averaging the daily averages on the six quietest days in the interval October - December 1964. After these zero levels are subtracted from the data at each station, the traces from the six stations are superposed and the magnitude of the envelope of the six traces is defined as the AE index.

The rationale behind this procedure is based upon the well known fact that auroral zone observatories undergo a pronounced diurnal variation in magnetic activity with a maximum of positive disturbance occurring shortly before local midnight and a maximum in negative disturbance occurring shortly after local midnight. In taking the envelope of the six stations, the stations located near midnight will be those most apt to contribute to the index. Provided an adequate longitude distribution of auroral zone stations is used, this procedure will eliminate the local time variation and yield an index which represents the universal time variations of the auroral electrojet. The auroral zone currents close partly through low latitudes so that

these currents strongly influence K_p . This means AE is closely related to K_p , (Davis and Sugiura 1966) the main differences being the time resolution and the fact that AE is a linear index whereas K_p is quasi-logarithmic.

The six stations used in the present study do not form an ideal distribution and this is a limitation of the study. The stations Sitka and Meanook are relatively close to College and Churchill, respectively, which are nearer the auroral zone, and thus Sitka and Meanook are rather infrequent contributors to the envelope except in rare cases when the electrojet moves far south of its normal position. The four remaining stations are well distributed in longitude yet large gaps still exist over eastern Canada, the North Atlantic, and the Soviet Union.

To check on the remaining local time dependence in the AE index, the average values of AE for each hour of Universal time were computed. Results showed almost a factor of two difference between different hours of UT. Although this could in part be due to a real UT dependence in geomagnetic activity, it is more likely that this is due to an inadequate longitude distribution of stations. It should be recognized in analyzing the following results that individual AE magnitudes may be in error (relative to some unknown ideal value) by something like a factor of two due to the imperfect distribution of stations.

Results

An example of the AE index and simultaneously measured magnetic fields is shown in figure 1. The top three traces represent the field magnitude F and solar ecliptic latitude and longitude angles θ and ϕ . This data is for orbit No. 23 on November 5-6, 1964 and it begins with the satellite outbound in the magnetosheath and ends with the satellite inbound in the magnetosheath. The low field region near apogee represents interplanetary space with shock crossings occurring at 11:55 and 2045 hours UT. An additional encounter with the magnetopause is apparent from 1400 to 1500 hours. Since field directions tend to be preserved as the interplanetary field is convected through the shock (Fairfield 1967), field directions in the magnetosheath and in interplanetary space are closely related and both may be compared with AE.

The fourth trace in figure 1 represents the superposition of the six stations whose envelope is defined as the AE index. The interval from 0900 to 1100 is typical of quiet times and the fact that six traces are near zero is indicative of the accuracy of the zero levels chosen for the various stations. Disturbed periods are apparent in several traces although the magnitudes are different, due primarily to differences in the longitudes of the stations. The bottom traces represent the disturbance magnitudes at the three polar cap stations (stations well north of the auroral zone) Resolute Bay, Mould Bay, and Alert. These polar cap magnitudes are defined as

$$PCM = ((X - X_0)^2 + (Y - Y_0)^2)^{\frac{1}{2}}$$

where X_0 and Y_0 are zero levels obtained from the six quiet days and X and Y are the values scaled every 2.5 minutes. These polar cap magnitudes correspond closely to the AE magnitudes since the auroral zone currents close over the polar cap. Sometimes the polar cap magnitudes increase slightly before AE and correspond better to the interplanetary field changes. The polar cap magnitude may be a better indicator of high latitude geomagnetic activity since it is less likely to be affected by spacial variations which help produce time variations in the beginning time of disturbance at auroral zone stations.

Figure 1 illustrates how southward fields (negative thetas) correspond to disturbed ground conditions as has been reported previously (Fairfield and Cahill, 1963; Wilcox et. al., 1967; Rostoker and Fälthammar, 1967). Four intervals of southward field beginning approximately at 11:05, 1430, 17:40 and 2300 are seen to correspond to increases in the AE index and polar cap magnitudes at approximately 11:45, 14:40, 17:45 and 23:15. Similarly northward fields tend to decrease the disturbance and correspond to quiet times. A phase lag between the southward motion of the field and the increase in the disturbance is apparent with the longer southward intervals from 1100-1300 and 1800-2030 producing the large disturbance.

Using the 5.46 minute averages and the AE index, the IMP 2 data was analyzed in two ways. The first approach was to define disturbed and quiet periods according to the ground observations and then determine the corresponding satellite field directional distributions for these intervals. A second approach was to take certain satellite field

conditions and investigate the ground conditions at the corresponding times. In all cases each 5.46 minute satellite field measurement was associated with the average of the two (or occasionally 3) AE points occurring after the center of the 5.46 minute satellite averaging interval.

The first approach where the satellite data was divided into two groups according to ground conditions was accomplished by calculating the median AE value for each orbit for the interval when the satellite was beyond the magnetopause. Satellite field measurements taken when AE was above the median for the orbit were placed in one group and measurements made with AE below the median were placed in a second group. Initially the median values ranged from 17 gammas to 209 gammas, however, since orbits with high medians would force quite disturbed measurements into the quiet group, (and low medians force quiet measurements into the disturbed group) the medians were adjusted and values greater than 100 gammas and less than 30 gammas were arbitrarily set to the values 100 and 30. Half the orbit medians were adjusted in this manner.

The latitude distributions of satellite field directions is shown in figure 2 (magnetosheath) and 3 (interplanetary). The distance from the origin in each latitude section indicates the relative density of field occurrences in that latitude range with the dotted circle designating an isotropic distribution. Fields in solar magnetic coordinates (Z along the dipole axis, X in the Z-earth sun line plane, and Y completing a right-handed orthogonal system) were used although a similar analysis in solar ecliptic coordinates gave similar results.

The distribution in figure 2a shows a relatively isotropic distribution (49% northward 51% southward) when all magnetosheath measurements are used. When these same measurements are divided into the two groups according to disturbed and quiet ground conditions, two very different distributions are obtained. When ground conditions are disturbed (Figure 2b) 67% of the fields are southward and 33% of the fields northward whereas for quiet conditions (Figure 2c) the fields are 60% northward and 40% southward. The fact that there are more points in the quiet group is a result of the adjustment of the median values. In figure 3 the same presentation is shown for interplanetary fields. Although the distribution of all measurements is more northward, the same tendency for southward fields to be associated with disturbance (and northward fields quiet conditions) is apparent.

The second approach used in comparing satellite and ground magnetic data was to separate the ground data into groups depending on the interplanetary (or magnetosheath) fields. Figure 4 shows the relative number of cases in each 10γ range of AE when the magnetosheath field is southward (solid line) or northward (dashed line). Although both curves have peaks near 20 gammas, the probability of occurrence of an AE value between 0 and 20 γ with the field northward is twice what it is if the field is southward. High AE values on the other hand correspond almost exclusively to southward values.

This same data is presented in a different form in figure 5. Here the relative number of cases with AE greater than the abscissa value

of AE is plotted as the ordinate. This figure shows that when the field is southward, 28% of the AE values are greater than 100γ whereas when the field is northward only 12% of the cases have AE greater than 100γ . This tendency for high AE values to be associated almost exclusively with southward fields confirms the conclusion of Fairfield and Cahill that southward fields are necessary for the production of a bay. The fact that a large number of small AE values are associated with southward fields in figure 4 at the same time supports their further statement that a southward field does not necessarily produce a bay. Rostoker and Fälthammar (1967) have also come to this same conclusion.

Figure 6 represents an attempt to separate out the relative importance of field magnitude and direction. All the AE data occurring when IMP 2 is in the magnetosheath has been divided into four groups depending on whether the magnetosheath field is northward, southward and greater than 15γ or less than 15γ . Previous work has indicated that both large fields and southward fields are associated with disturbance and indeed the curve corresponding to this case in figure 6 is associated with the largest disturbance. The opposite case of weak northward fields and quiet conditions is also confirmed by the dotted curve in figure 6. Contrasting these two curves shows that with weak northward fields hardly any AE values larger than 200γ occur whereas with strong southward fields over 20% of the cases have AE greater than 200γ . This indicates appreciable sensitivity of auroral zone currents to the interplanetary magnetic field.

The two remaining curves for the contradictory cases of large but northward fields and small but southward fields are nearly similar. In this sense we can conclude that magnitude and direction are of nearly equal importance in influencing geomagnetic activity.

Figure 7 again illustrates the number of cases of AE greater than the abscissa for the cases when the component of the magnetosheath field perpendicular to the solar magnetic equatorial plane is greater than 9γ and less than -9γ . The extreme difference of these curves provides further confirmation of the importance of field direction and the necessity of a southward field for producing large AE values.

Although the data in figures 4-7 is all from the magnetosheath, similar analyses have been performed on the interplanetary data with similar results. This is to be expected since the field direction tends to be preserved when the interplanetary fields are convected through the shock. (Fairfield 1967).

Discussion and Conclusions

The solar wind plasma is undoubtedly the energy source for the ionosphere currents producing geomagnetic disturbance, yet the results of this paper show that the relatively low energy density interplanetary magnetic field plays an inordinately large role in the energy transfer. Of the theories proposed to explain geomagnetic activity, the one best able to explain these results is that of Dungey (1961, 1963, 1967) and Petchek (1964). Their basic idea is that a southerly directed interplanetary field may become connected to the geomagnetic field at a neutral point on the sun ward side of the magnetosphere. These connected interplanetary field lines are then carried back into the magnetospheric tail where the interplanetary field disconnects at a night side neutral point. The resulting plasma flow is toward the sun in the magnetosphere and away from the sun in the magnetosheath and it has associated with it an electric field $E = \frac{-V}{c} \times B$ which drives the ionospheric currents which produce the high latitude magnetic activity. Northward directed interplanetary fields preclude reconnection, inhibit the flow, thus reducing the electric field which is possible with a southward electric field.

The results of this paper show a definite tendency for disturbance to be associated with southward fields and quiet times with northward fields in spite of several factors which would tend to make these results less clear. One of these factors is the imperfect nature of AE due to the limited number of stations and the spacial variations of the current patterns. These spacial variations produce displacements

on the magnetograms which are subsequently interpreted as universal time variations in AE. There is also the possibility that a southward field might be producing a disturbance which is not adequately reflected in the AE index. Perhaps a more important limitation concerns the effect of a north-to-south direction change. As was noted by Fairfield and Cahill (1966) and is confirmed in scanning the IMP 2 data, the effect of this north-south change is to decrease the level of disturbance, but over a time interval of half an hour or more. This means that a northward field may be associated with a large (but decreasing) AE value. Any similar phase lags between changes of the interplanetary field and response of the ground activity would likewise tend to reduce the clarity of the results since field measurements were compared with essentially simultaneous ground measurements.

Although quantitative calculations have not yet been performed regarding a time delay between changes in the interplanetary field and response of the ground activity index, the conclusions of Fairfield and Cahill (1966) are substantiated by scanning the IMP 2 data. A relatively infrequent sudden north-to-south change in the interplanetary field invariable produces an increase in ground activity within a few minutes after the change is observed at the spacecraft. This change is not necessarily a large change which would warrant the term bay or substorm. Gradual north-south changes produce similar increases but it is more difficult to discern time delays because of their gradual nature. A prolonged period of southward field generally increases the disturbance level and bays or substorms may occur. Since the southward field component is only a necessary condition for producing

a bay the results do not appear to be inconsistent with the ideas of Heppner, et al., (1967) who argue that sudden bay commencements may be predicted shortly in advance by observing auroras and hence cannot be produced by an unpredictable change in the incoming interplanetary medium. It appears possible that a southward field is necessary to create the conditions for a bay yet some other process in the tail (Alkinson, 1966) or the ionosphere (Heppner, et. al., 1967) produces the actual bay commencement.

The result that strong southward fields are most efficient in producing disturbance is consistent with the reconnection model since the amount of southward flux carried up to the magnetosphere is an important parameter. Similarly, weak northward fields correspond to a small amount of flux which is oriented in the wrong direction for reconnection. The fact that strong northward fields and weak southward fields correspond to approximately equivalent disturbance is probably due mainly to the time lag effect described above. Strong northward fields and strong southward fields tend to occur on the same days (typically reversing on a time scale of hours) and the time lag effect will be important at these times. Strong fields also occur during times of high velocity and density when other mechanisms such as magnetospheric compression and wave generation may contribute to the ground activity. The higher AE values associated with strong northward fields may be partially due to these other effects.

Although solar wind velocity is known to be important in producing disturbance (Snyder, Neugebauer and Rao, 1963) it seldom varies by more than a factor of two which is small compared to the changes in the

magnetic field. Solar wind velocity- K_p studies on a 3 hour time scale would tend to smooth out the magnetic field effects since direction changes over shorter time scales are very common. Undoubtedly the field directions effects are responsible for the considerable scatter in the V vs. ΣK_p plot of Snyder, Neugebauer and Rao (1963). Since appreciable velocity changes occur on a time scale of days and magnetic field direction changes typically on a time scale of hours, it is attractive to picture the velocity controlling the general level of activity and the magnetic field producing an important modulating effect. The use of median values in separating quiet and disturbed days in this study suppresses the long term velocity changes.

TABLE 1

ARCTIC MAGNETIC OBSERVATORIES

	Geographical		Geomagnetic		Zero Level (gammas)	
	Latitude	Longitude	Latitude	Longitude	X	H
Auroral Zone						
Leirvogur	64°11'N	21° 41' N	70.2°N	71.0°		12040
Kiruna	67°50'N	20° 25' E	65.3°N	115.7°	11038	
College	64°51'N	147.51' W	64.5°N	255.4°		12842
Sitka	57°03'N	135°20' W	60.0°N	275.4°		15716
Meanook	54°37'N	113°20' W	61.8°N	301.0°		13120
Fort Churchill	58°44'N	94° 15' W	68.6°N	322.6°	6854	
Polar Cap						
					X	Y
Alert	82°33'N	62° 20' W	85.9°N	168.7°	733	-3748
Mould Bay	76°12'N	119°24' W	79.1°N	255.4°	1019	-2208
Resolute Bay	74°41'N	94.50' W	83.1°N	287.7°	123	-808

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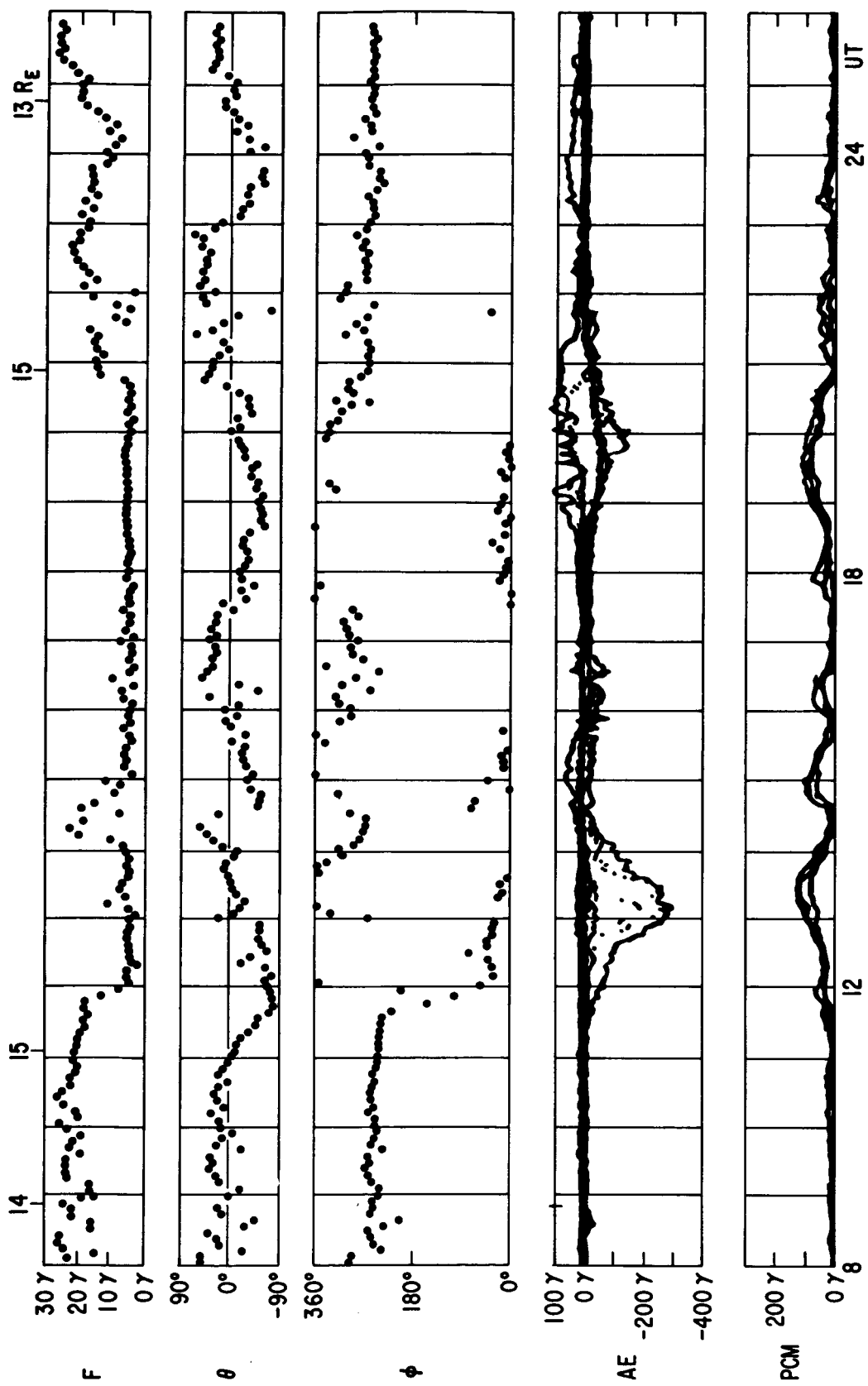
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FIGURE CAPTIONS

- Figure 1 IMP 2 magnetic field data for orbit 23 in solar ecliptic coordinates. Also shown are the superposition of traces from six stations whose envelope is defined as the AE index. The bottom traces are the magnitudes of the polar cap disturbance at three stations. Disturbed periods on the ground correspond to periods of southward field (negative θ) observed at the spacecraft.
- Figure 2 The latitude distribution of magnetosheath field directions are shown for all measurements (a) and when ground conditions are disturbed (b) and quiet (c). Disturbed conditions correspond to a predominantly southward distribution and quiet conditions to a predominantly northward distribution.
- Figure 3 Same as figure 2 for interplanetary fields.
- Figure 4 Number of occurrences of AE in 10 gamma ranges when the field is northward (dashed line) and southward (solid line). A high proportion of low AE values occur when the field is northward compared to the number occurring when the field is southward.
- Figure 5 The ordinate represents the number of cases with AE greater than the abscissa when the field is negative (dashed line) and positive (solid line). Virtually all AE values greater than 300γ are associated with southward fields.
- Figure 6 The number of cases with AE greater than the abscissa for four groups depending on direction and magnitude. The greatest disturbance is associated with large southward fields and the

most quiet conditions with weak northward fields. The large northward and weak southward fields nearly correspond suggesting equal importance of magnitude and direction.

Figure 7 Number of cases with AE greater than the abscissa when the component of the magnetosheath field perpendicular to the solar magnetic equatorial plane is greater than 9γ northward (solid curve) and southward (dashed curve).



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FIGURE 1

MAGNETOSHEATH IMP-2, ORBITS 1-39

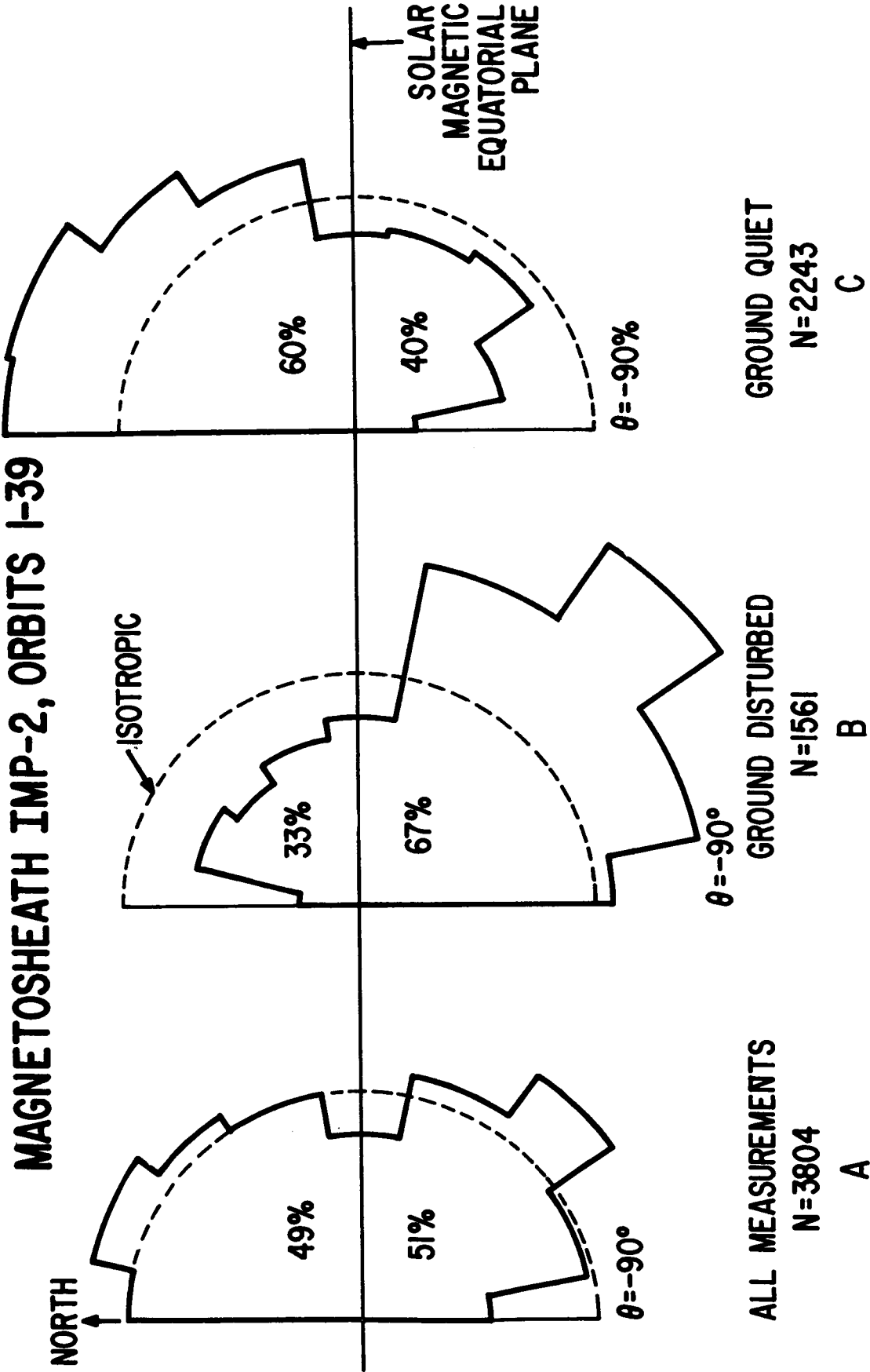


FIGURE 2

INTERPLANETARY IMP-2, ORBITS 1-39

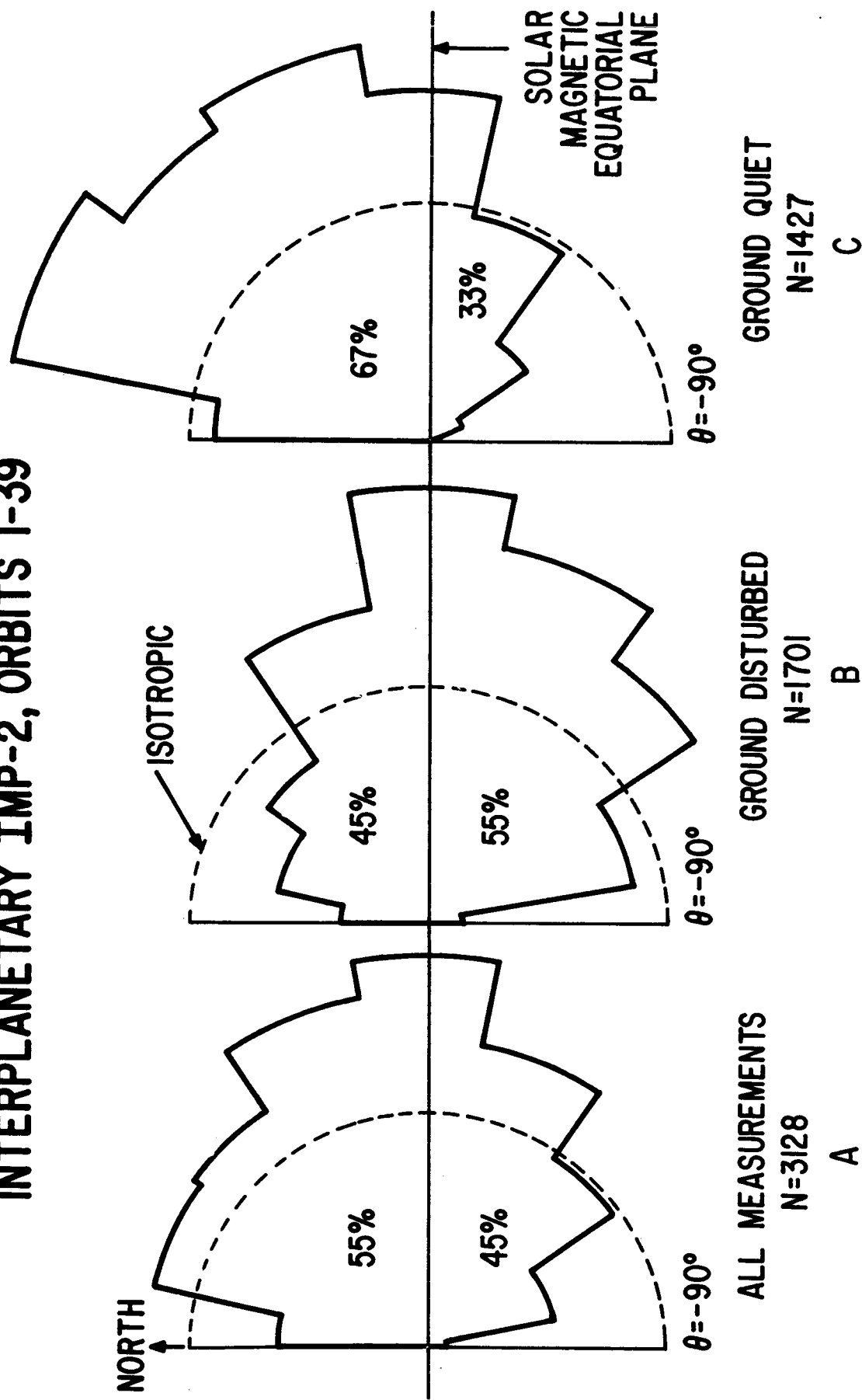


FIGURE 3

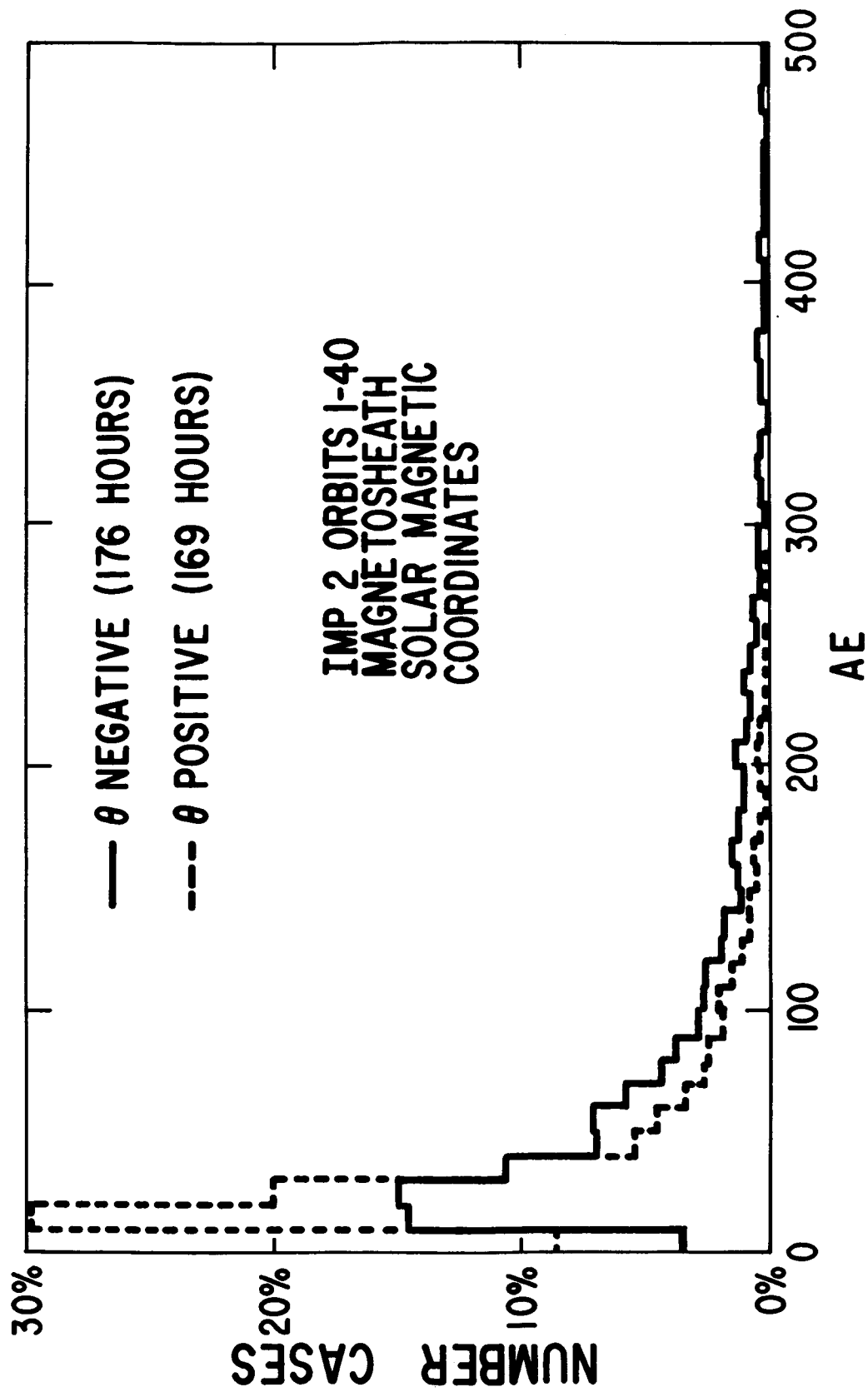


FIGURE 4

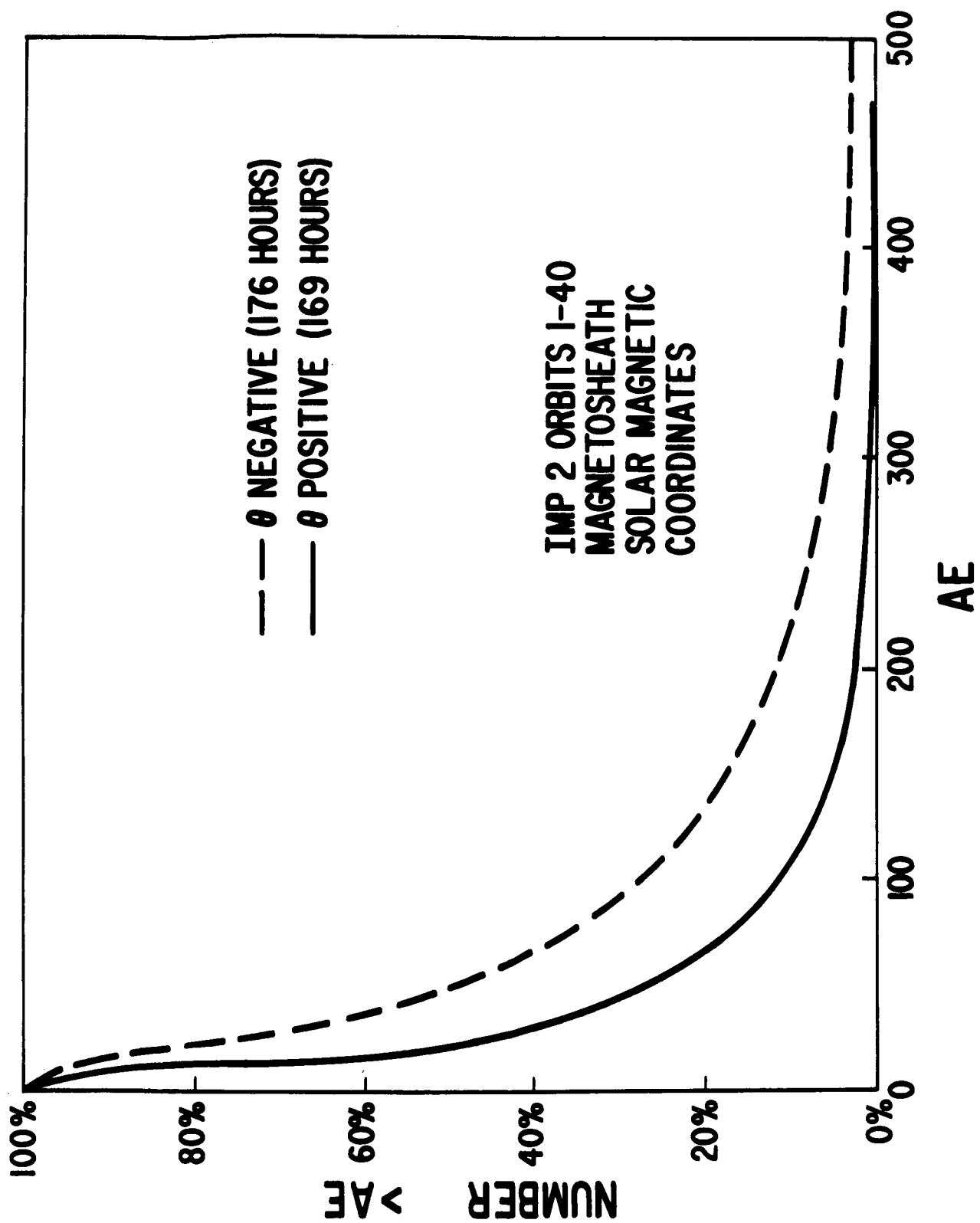


FIGURE 5

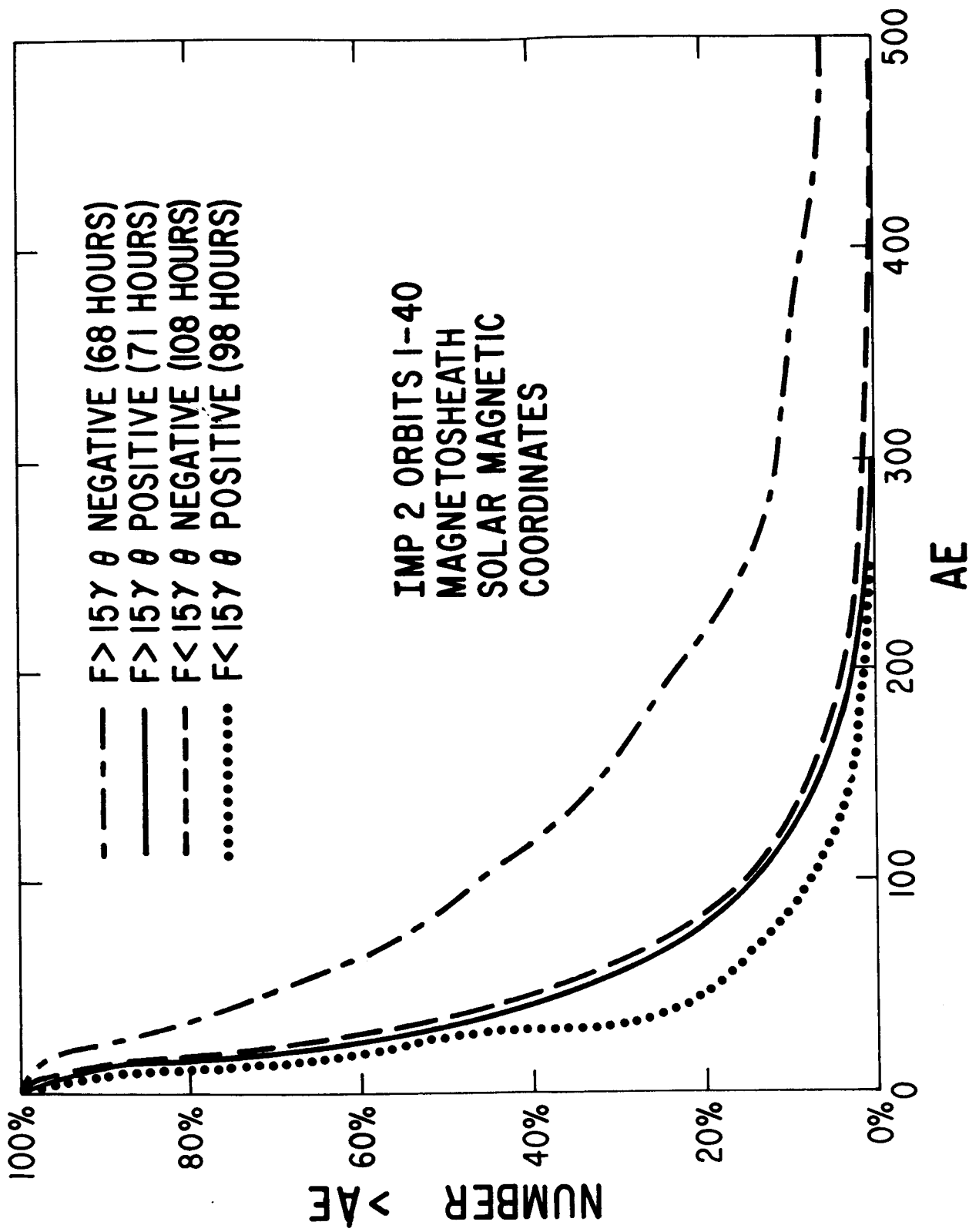


FIGURE 6

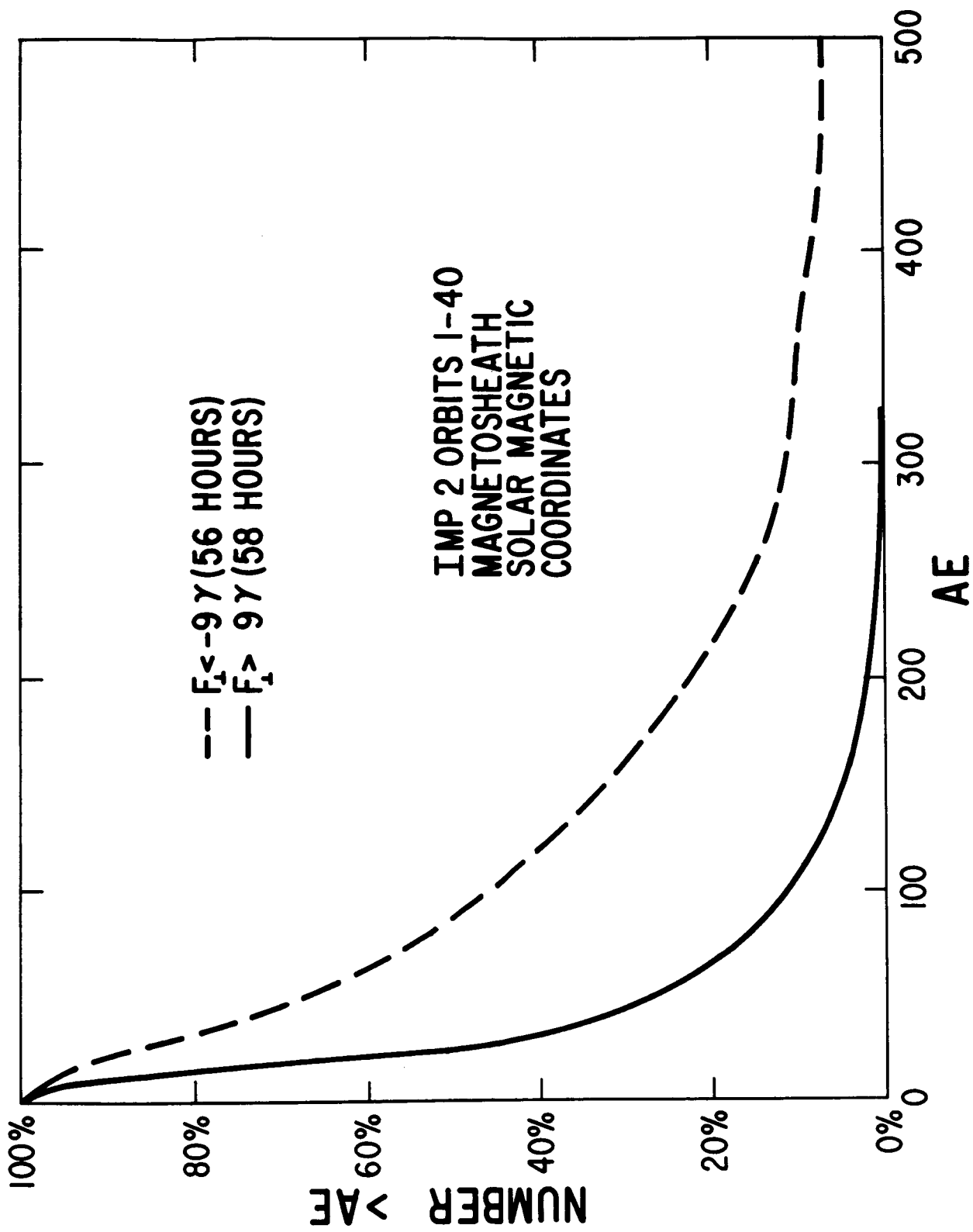


FIGURE 7